

Automated registration and orthorectification package for Landsat and Landsat-like data processing

Feng Gao,^{a,b} Jeffrey G. Masek,^b and Robert E. Wolfe^b

^a Earth Resources Technology Inc., 10810 Guilford Road,
Annapolis Junction, MD 20701, USA

^b NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

Abstract. Precise registration and orthorectification of remote sensing images are the basic processes for quantitative remote sensing applications, especially for multi-temporal image analysis. In this paper, we present an automated precise registration and orthorectification package (AROP) for Landsat and Landsat-like data processing. The Landsat and Landsat-like satellite images acquired from different sensors at different spatial resolutions and projections can be re-projected, co-registered, and orthorectified to the same projection, geographic extent, and spatial resolution using a common base image through a combined resampling strategy; this allows us to perform multi-temporal image analysis directly. This paper presents and tests the AROP package on Landsat and Landsat-like data. The package is now freely available from our research web site.

Keywords: orthorectification, precise registration, projection, Landsat, ASTER.

1 INTRODUCTION

Landsat and Landsat-like data consist of long-term mid-resolution satellite data that are extremely useful for various remote sensing applications [1,2]. The Landsat satellite series has continuously provided earth observation data since the early 1970s. Despite the Scan Line Corrector (SLC)- failure in Landsat 7 and the considerable age of Landsat 5, Landsat data are still the major mid-resolution data sources for the remote sensing community. These data are supplemented, but cannot fully be replaced, by other currently operating Landsat-like sensors [2,3] such as the Charge Coupled Device (CCD) camera aboard the China-Brazil Earth Resources Satellite (CBERS), the Linear Imaging and Self Scanning sensor (LISS-III) and Advanced Wide Field Sensor (AWiFS) aboard the Indian Remote Sensing Satellite (IRS), and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) aboard NASA's Earth Observing System (EOS) Terra spacecraft. The synergy among different mid-resolution sensors is not only valuable for maintaining Landsat data continuity but also for a more robust land monitoring system that requires frequent observations [2].

Accurate geo-referencing information is a basic requirement for combining remote satellite imagery with other geographic information. To detect changes in time-series satellite images, it is extremely important for the images to be precisely co-registered and orthorectified, so that images acquired from different sensors and dates can be compared directly.

Precise registration relates satellite images to the ground reference based on carefully selected ground control points between the image and corresponding ground objects. Co-registration matches two images based on the tie points in the images. Although most commercial remote sensing software packages provide precise registration or co-registration, the selection of control points or tie points needs to be done manually. This is a time-consuming process that is not feasible for a large amount of data processing. Even though some satellite data are precisely registered and orthorectified, mismatches of up to a few pixels are common in those data sources [4].

The topographical variations of the earth's surface and the satellite view zenith angle affect the pixel's distance projected onto the satellite image. The distortion inherent in the image is determined by topographical elevation. For example, an off-nadir view of 5 degrees at a site with a terrain height of 1000 meters can cause displacement of 120 meters (about 4 Landsat Thematic Mapper (TM) pixels). The orthorectification process is used to correct the pixel displacement caused by the topographical variations at the off-nadir viewing and to make the image orthographic, with every pixel in its correct location regardless of elevation and viewing direction [5].

In this paper, we present an automated registration and orthorectification package (AROP) developed for Landsat and Landsat-like data processing. It uses precisely registered and orthorectified Landsat data (e.g., GeoCover [6] or recently released free Landsat archive data from the USGS EROS data center) as the base image to co-register and orthorectify the warp image and thus to make geo-referenced time-series images consistent in the geographic extent, spatial resolution, and projection. This package has been tested on the Landsat Multi-spectral Scanner (MSS), TM and Enhanced TM Plus (ETM+), Terra ASTER, CBERS CCD, and IRS-P6 AWiFS data. It has been used in time-series stacks of Landsat imagery analysis for reconstructing forest disturbance history [4]. The AROP package is now freely available from our research web site http://ledaps.nascom.nasa.gov/ledaps/ledaps_NorthAmerica2008.html.

2 KEY TECHNIQUES

2.1 Automated Registration

Time-series image analysis involves direct comparison of pixel at same location and requires precise registration [7]. Traditionally, precise registration has relied on manually selected stable ground control points such as bridges and road intersections. Co-registration of two images relies on pairs of tie points that relate identical targets in each image. Since co-registration is based on similar images, the selection of tie points can be automated. Given a registered and orthorectified base image the AROP package co-registers and optionally orthorectifies a second image (the "warp" image). Because the base image is geo-referenced, the output registered image will also be a geo-referenced image.

Tie points can be based on image feature or area-based matching [5,8]. Feature-based approaches match tie points based on features extracted from the two images, such as points or edges. These features must be identical and unchanged. This condition may not be satisfied in areas with significant landscape changes. To solve this problem, a recent extension of the feature-based approach uses pseudo invariant features (PIF) [9,10]. In contrast, the area-based approach checks for similarity between two images using a small moving chip window [5]. The location with maximum correlation in the search window reveals the location of the tie point [11].

The AROP package adopts an area-based image correlation approach. The initial matching points in the base image are set up systematically using a fixed grid, with the grid spacing defined in the input parameter file. The initial location of a matching tie point in warp image is estimated based on the given image coordinates:

$$wx = (bx \text{ res}_{base} + (ulx_{base} - ulx_{warp})) / \text{res}_{warp} , \quad (1)$$

$$wy = (by \text{ res}_{base} + (uly_{base} - uly_{warp})) / \text{res}_{warp} , \quad (2)$$

where coordinate (bx, by) is the initial pixel location in the base image. Coordinate (wx, wy) is the initial guess of the tie point location in the warp image. Coordinates (ulx_{warp}, uly_{warp}) and

(ulx_{base}, uly_{base}) are the upper left coordinates for the warp image and the base image, respectively. The res_{warp} and res_{base} variables refer to the pixel resolution for the warp and the base image, respectively. The accuracy of the initial guess (wx, wy) depends on the accuracy of the coordinates in the warp image. If the warp image is perfectly coregistered to the base image, then the initial guess will represent the actual tie point location. However, in most cases, the systematically corrected (e.g. Landsat Level 1G) satellite images carry geolocation errors, so the initial guess is not the actual location. The AROP package will search for the best matching location between two images within a defined search distance.

For a defined maximum search distance (ms) around location (wx, wy) , the cross-correlation [12] of the central pixel (m, n) in a defined chip window size (cs) between two images can be computed as

$$r_{mn} = \frac{\sum_{i=m-cs/2}^{m+cs/2} \sum_{j=n-cs/2}^{n+cs/2} (A_{ij} - \bar{A})(B_{ij} - \bar{B})}{\sqrt{\left(\sum_{i=m-cs/2}^{m+cs/2} \sum_{j=n-cs/2}^{n+cs/2} (A_{ij} - \bar{A})^2 \right) \left(\sum_{i=m-cs/2}^{m+cs/2} \sum_{j=n-cs/2}^{n+cs/2} (B_{ij} - \bar{B})^2 \right)}}, \quad (3)$$

where r_{mn} is the cross-correlation coefficient of chips containing the central pixel (m, n) from the base image (A) and the warp image (B). The cross-correlation calculation normalizes the two images by removing the average brightness value (e.g. \bar{A}), thus suppressing local differences between the two image windows due to calibration or illumination variations. Pixel (m, n) is located within the search window and satisfies the following conditions:

$$wx - ms \leq m \leq wx + ms \quad \text{and} \quad wy - ms \leq n \leq wy + ms.$$

Fig. 1 demonstrates the tie point searching process. The initial guess of the tie point location (wx, wy) is first computed using Eqs. (1) and (2). The correlation coefficient is computed for each pixel (m, n) within the maximum search distance (ms) using the predefined chip window size (cs). The chip window for the base image (A) is fixed around the tie point (px, py) in the base image. The chip window size (cs) should be large enough to contain the spatial features of images but small enough to exclude internal distortion within the chip. The default value for the chip window size is 11 by 11 pixels, but it can be adjusted in the tie point control file (see Appendix A.2).

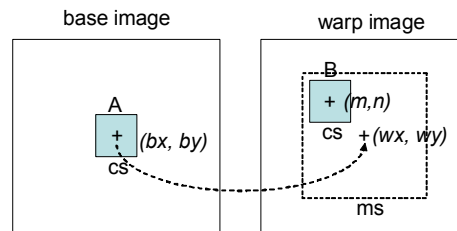


Fig. 1. Diagram for tie point searching.

In the AROP package, the maximum search distance (ms) is adjusted to a smaller appropriate value after several successful attempts. The new upper left coordinate for the warp image is estimated from successful tie points and then a new location for the tie point in the warp image is estimated based on the updated coordinates of the warp image. Generally, the new location is more accurate; thus, a smaller search distance is sufficient and can

dramatically reduce computation time (the computation time for area-based approach is cs^2ms^2 [5]).

From a list of computed correlation coefficients within the small subset window ($-ms, +ms$), the AROP package determines a good quality match using two criteria: 1) a high maximum correlation coefficient and 2) a small number of high cross-correlation coefficients. The high cross-correlation coefficient alone is not enough to determine a good quality tie point. For a uniform area, such as a forest, grassland, or water body, high correlation coefficients are frequent, as shown in Fig. 2a. An ideal tie point should show only a few high correlations within the search area, as shown in Fig. 2b.

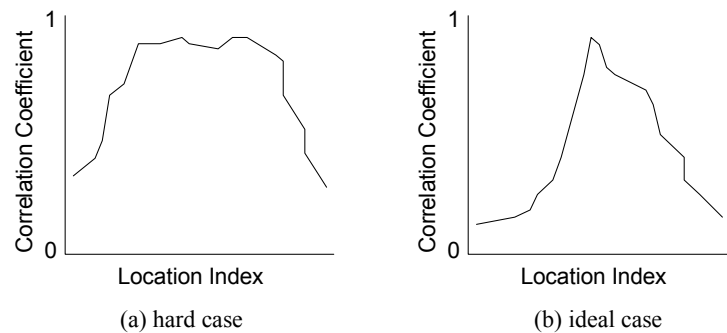


Fig. 2. The detection accuracy of the tie points relies on the individual search area. A radiometrically homogeneous region may produce a flat diagram of correlation coefficient (a). A more spatial/structural variable region may produce a sharp diagram (b), which is more appropriate for tie point selection.

The tie point locations are saved as integer numbers of row and column at this stage, which may not represent the actual best (sub-pixel) matching location. The AROP package computes the best matches at the sub-pixel location based on the cross-correlation coefficients of neighboring pixels of the tie point. It estimates the best matching location at sub-pixel resolution using a quadratic bivariate polynomial function. Assuming that the correlation coefficients of neighbor point are saved as $f(i, j)$, the correlation can be simulated with a bivariate polynomial function

$$f(i, j) = c_0 + c_1i + c_2j + c_3i^2 + c_4ij + c_5j^2, \quad (3)$$

where (i, j) is the pixel location and $f(i, j)$ is the cross-correlation coefficient for this pixel. Assuming that the central location of matrix is $(0, 0)$, both i and j vary from $-s/2$ to $s/2$, where s is the defined matrix size to save neighboring pixels. Parameters c_0, c_1, c_2, c_3, c_4 , and c_5 are the coefficients for the bivariate polynomial function. They can be retrieved using the least square fitting approach. The function has a maximum value if parameters satisfy the following conditions:

$$4c_3c_5 - c_4^2 > 0 \text{ and } c_3 < 0.$$

The sub-pixel location (i', j') with the maximum cross-correlation coefficient can be computed as

$$i' = (c_2c_4 - 2c_1c_5) / (4c_3c_5 - 2c_4^2), \quad (4)$$

$$j' = (c_1 c_4 - 2c_2 c_3) / (4c_3 c_5 - 2c_4^2). \quad (5)$$

Note that since the base image is orthorectified, the coordinates of the tie points from the base image are already corrected for terrain effects. The coordinates of the tie points from the warp image, however, may or may not be corrected. If not, these coordinates must be orthorectified before the actual matching test. The orthorectification process will be discussed in the next section.

Once enough tie points are found, the AROP attempts registration with the coordinate shift (translation) option. For imagery with few internal distortions, such as Landsat TM/ETM+ L1G data, shifting the upper left coordinate is sufficient for co-registration. If the shift attempt fails, i.e., the matching error is larger than the acceptable accuracy, then the AROP will perform the bivariate polynomial function through an iterative process. In each iteration, the AROP eliminates the least matching tie point until the root mean square error (RMSE) from the remaining tie points satisfies the defined criteria (default value of 0.75 pixel). The iteration starts from a low degree (linear) polynomial function. If the linear polynomial function fails, i.e., the number of remaining tie points reaches the minimum requirement (default value of 10 points), and the RMSE is still larger than the predefined criteria, then the AROP package attempts a higher degree polynomial (quadratic) function.

The criteria for tie point searching, selection, and polynomial transformation are defined as the AROP tie point control parameters and can be adjusted according to specific satellite data and user specifications. We will explain the detailed parameters in the Appendix.

2.2 Orthorectification

The orthorectification process is used to correct pixel displacement caused by off-nadir viewing of topography (ie. Locations above the geoid height). The AROP package adopts the terrain correction algorithm developed in the Landsat 7 Image Assessment System (IAS) [13]. The displacement from terrain effect Δx can be computed in a series of geometric transformations as follows:

$$\theta = x / r, \quad (6)$$

$$\sin(\alpha) = (r + s) \sin(\phi + \Delta\phi) / r, \quad (7)$$

$$\tan(\Delta\phi) = \frac{(r + s) \sin(\phi) (1 - (r + h) / r)}{(r + h) \sqrt{1 - (r + s)^2 \sin^2(\phi) / r^2} - (r + s) \cos(\phi)}, \quad (8)$$

$$\sin(\phi) = r \sin(\theta) / \sqrt{r^2 + (r + s)^2 - 2r(r + s) \cos(\theta)}, \quad (9)$$

$$\Delta x = r(\alpha - \theta - (\phi + \Delta\phi)). \quad (10)$$

The known values are: the radius of the earth referenced ellipsoid at the scene center r ; the distance from the pixel center to the nadir track line x , the altitude of the satellite above the ellipsoid s , and the terrain elevation h . The unknown values are: the earth centered angle of the observation point relative to nadir θ , the angle defined by the line from satellite to observation point and the line from earth center to observation point α , the satellite centered angle of the observation at the top of the terrain relative to the hypothetical observation of the sea level at same point $\Delta\phi$, and the satellite centered angle of the observation point relative to nadir ϕ ; The AROP package computes the earth's radius based on the World Geodetic

System 84 (WGS84) datum, which is consistent with the GeoCover or Global Land Survey (GLS) Landsat data set [14].

The AROP assumes constant satellite altitude for a given satellite. The altitude for a new satellite can be added to the package as a new input parameter. The nadir track for the Landsat Worldwide Reference System 2 (WRS-2) can be computed from predefined coordinates for four corners [15]. If the actual corner coordinates of the original warp scene are not available (e.g., Landsat data in the WRS-1 system), the AROP analyzes the satellite nadir track from image, assuming that the middle line of the swath is the nadir track when sensor pointing angle equals zero (Fig. 3). If the sensor pointing angle is not zero (e.g. ASTER data), then the nadir track will be adjusted according to the pointing angle and direction. This can be implemented by scanning the image and finding the valid image edge. A linear fitting function is then built based on the edge pixels using a least square fitting approach. The slope of this fitting function and the nadir location of the scene are used to determine the nadir track equation. The nadir track equation computed from either the given WRS-2 corners or the left (or right) image edges can be expressed as: $ai + bj + c = 0$, where i and j are the row and column index, respectively. The distance x from a given pixel $P_0 (i_0, j_0)$ to the nadir track can be computed as

$$x = \frac{|ai_0 + bj_0 + c|}{\sqrt{a^2 + b^2}}. \quad (11)$$

The location of the pixel to the nadir track line determines the correction direction. A positive terrain elevation (above sea level) expands the image outward to the nadir track line. The further away that the pixel lies from the nadir line, the more displacement that will occur. The orthorectification process corrects the terrain effect and brings the pixel back to the geolocation as if observed from the nadir view. Thus, if a pixel is on the right side of nadir track line (e.g., P_0 : $ai + bj + c > 0$), then the correction should move toward the nadir track line and should be assigned a negative sign; otherwise, it should be assigned a positive sign.

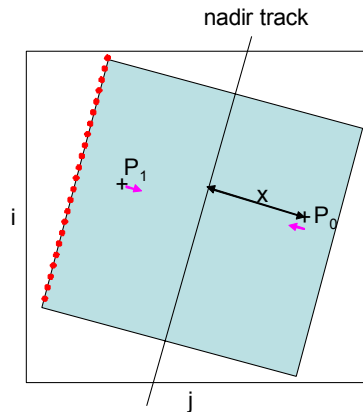


Fig. 3. The nadir track equation ($ai + bj + c = 0$) of a satellite scene can be derived from the detected edge pixels (red dots) and the central pixel of scene. The terrain displacements for pixels P_0 and P_1 are corrected by moving toward the nadir track line.

2.3 Registration and Orthorectification Verification

Errors of initial registration and orthorectification come mainly from two sources. First, the tie points for co-registration based on the un-orthorectified warp image and the orthorectified

base image may be falsely detected if there are distortions inside the control chip. These distortions may be caused by the topographic effects or land cover changes. Second, inaccurate terrain elevation due to inaccurate coordinates of the original warp image or DEM data resolution may cause inaccurate pixel locations in the output image. Thus, verification and correction are necessary for registration and orthorectification.

The AROP package verifies results by comparing the initial orthorectified image and the base image. Systematically distributed tie points between the initial orthorectified result and the previously orthorectified base image are extracted using the same area-based matching approach from the registration process. These tie points are grouped into four sub-regions: upper left, upper right, lower left, and lower right. At least half of the tie points from the four regions must pass the tie point matching test (i.e., errors are less than a predefined threshold). Otherwise, the AROP package will revoke a higher degree polynomial function for registration and re-run the orthorectification.

3 IMPLEMENTATION

3.1 Pyramid registration

A drawback of the area-based tie point searching approach is that it is very time consuming [5]. If there are large geolocation errors in the warp image, then the projected tie point location from Eqs. (1) and (2) will be far away from the actual location. In order to find the corresponding tie points, a large search distance must be defined. Increasing the search distance not only requires more computation time but also risks false detection.

To reduce search time and the risk of false detection, the AROP package uses a two step (layer) pyramid registration process that first computes and applies a coarse preliminary registration before computing and applying the (second) precise registration. Preliminary registration is based on coarse resolution images that are aggregated from the original images via averaging. The base and warp images at original resolution are first aggregated to the coarse images in the same spatial resolution. The spatial resolution of coarse images is adjustable as a tie point control parameter with default value of 10 times coarser than that of original image. Preliminary registration is performed using coarse resolution images with the same tie point search method discussed in Section 2.1.

As spatial resolution is reduced, the search distance (in pixels) decreases, and the preliminary registration on coarse resolution images is more efficient. The AROP package attempts to shift the upper left coordinate during preliminary registration; it does not perform higher degree polynomial correction or actual resampling at this point. The new upper left coordinate computed from preliminary registration is then used to update the warp image. Because small variations and noise in fine resolution images can be smoothed out in the aggregated images, area-based automatic registration is even more effective for coarse resolution. Although the accuracy from preliminary registration is not as good as that from precise registration, the updated upper left coordinate still provides better accuracy than the original one, especially for data sources that contain large geolocation errors. If geolocation errors found during preliminary registration are less than the defined accuracy, then the AROP package will keep the original coordinate for the upper left corner.

Precision registration at full resolution is applied if preliminary registration succeeds. Precision registration uses the updated coordinate as the new coordinate for tie point searching and orthorectification. The maximum search distance will be adjusted to a smaller value (in a few coarse resolution pixels) for precise registration. Our tests show that the pyramid registration option works well for scenes with large geolocation errors, even up to a third of a satellite scene dimension. The pyramid registration strategy provides an effective and accurate registration solution for early satellite data sets with large geolocation errors or data sets with unidentified geolocation accuracy.

3.2 Multiple data source registration

Multi-temporal images from Landsat and Landsat-like sensors are extremely useful for time-series analysis. However, data sources may or may not be registered and orthorectified, and they may be saved in different spatial resolutions and projections. Even for data sets from the same satellite sensor, geolocation accuracy and spatial resolution may vary depending on the processing requirements and system. For example, the Landsat GeoCover data set uses 28.5 meters as the final output pixel resolution, while many existing Landsat L1G data are distributed at 30 meter spatial resolution. Some Landsat data may be stored in the swath orientation direction, which needs to be rotated to map north.

The AROP package provides the capability to handle data sources with different spatial resolutions, projections, and orientations. In order to process multiple data sources using the same procedure for one data source, we introduce the working space concept. The working space keeps the base, warp, and output images in the same spatial resolution and projection. Data sources with different spatial resolutions, projections, and orientations are processed to a common spatial resolution and projection in the working space (Fig. 4). In this way, we can process data from different sources. For example, we can define the GeoCover Landsat TM/ETM+ image as a base image to orthorectify coarse resolution images, such as IRS AWiFS data and Landsat MSS data. The AROP package will aggregate the Landsat GeoCover image to a coarse resolution image; precision registration, orthorectification, and verification will be performed at the working space resolution. If the warp image has a fine spatial resolution, such as Terra ASTER or CBERS CCD data, then the working space will use the Landsat GeoCover spatial resolution as the spatial resolution. Once initial orthorectification and registration are verified and passed (in the working space), the final orthorectification will be revoked and processed in the defined output spatial resolution.

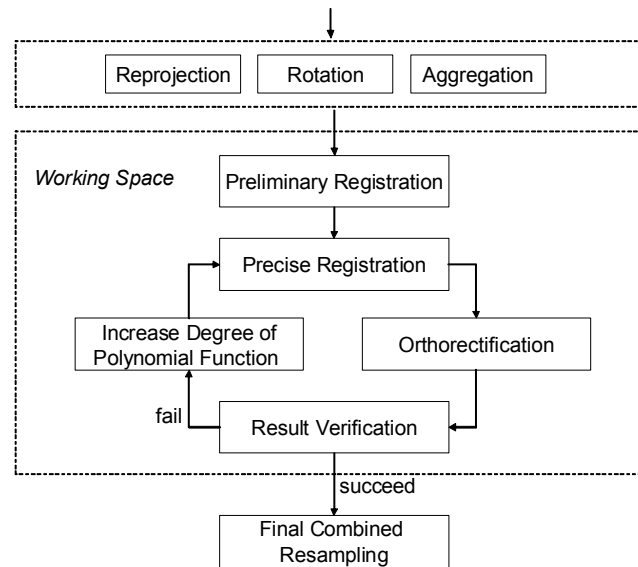


Fig. 4. Iterative processing flow for the AROP registration and orthorectification package. The working space is created for input and output with different spatial resolutions, projections, or orientations.

Note that the initial registration, orthorectification, and verification processes are based on a single selected band, which should be sensitive to surface types but not to atmospheric effects. We choose the Landsat TM/ETM+ band 5 (or band 4 to match MSS band 3) for initial

registration and orthorectification attempts and for later output verification. All preprocesses, including map rotation, reprojection, and image aggregation, are based on the selected band for computing efficiency. Only the final orthorectification and resampling processes use all of the input bands.

The geolocation accuracy of the output is controlled by the base images. For example, if Landsat GeoCover data are used as the base image to orthorectify a fine resolution image, then the output geolocation accuracy will be determined by the GeoCover data, even though the output spatial resolution can be defined in a finer spatial resolution. It is more appropriate to have a fine resolution image as the base image.

3.3 Combined resampling strategy

Multiple resampling processes reduce image quality and geolocation accuracy. The AROP package combines reprojection, rotation (if necessary), registration, and orthorectification into one resampling processing. The original warp image is first transformed (reprojected and/or rotated) to the working space for co-registration and orthorectification testing. Once registration and orthorectification verification pass in the working space, the final combined resampling process traces each pixel location in the output image backward through a series of necessary transformations, including registration, orthorectification, reprojection, and rotation. It then retrieves the pixel location in original warp image. The final registered and orthorectified outputs are resampled once from the original warp image.

The AROP provides four resampling approaches: the nearest neighbor approach, the bilinear interpolation approach, the cubic convolution approach, and the area-weighted aggregation approach. The first three approaches are typical for remote sensing image processing. The area-weighted aggregation option is designed for the fine resolution warp image to obtain coarse resolution orthorectified outputs. Coarse resolution outputs are computed by averaging fine resolution pixels weighted by overlapping area. For example, we may use Landsat GeoCover data as the base image in 28.5 meter resolution to co-register and orthorectify finer ASTER data in 15 meter resolution and then save the output in 28.5 meter resolution in order to match Landsat imagery for direct comparison. In this example, the AROP package first runs the necessary preprocessing, such as map rotation and reprojection, and then normalizes the input spatial resolution to Landsat and performs initial registration, orthorectification, and verification in working space resolution (Fig. 4). After verification, temporary orthorectified outputs are processed in ASTER's original spatial resolution, regardless of the defined output resolution, in order to preserve image information. Then, the temporary orthorectified outputs are aggregated to the Landsat resolution. In this case, the area-weighted aggregation is more appropriate than the nearest neighbor resampling approach, which uses a smaller footprint (ASTER pixel) to represent a larger footprint (Landsat pixel).

3.4 Iterative processing

As mentioned in Section 2.3, the AROP package will verify the orthorectified result with the base image and re-run orthorectification and registration if verification fails. It will increase the degree of the polynomial function in each iteration and then re-run registration and orthorectification, as shown in Fig. 4. If the warp image has been processed accurately for systematic distortions, then a linear polynomial function is adequate for co-registration. Although a high degree function is not suggested, we found that the quadratic polynomial function was necessary for some early Landsat MSS images. We also found that although approximately two-thirds of the Landsat TM/ETM+ scenes required only one processing; one-third failed initial verification and required second registration and orthorectification iteration with first degree polynomial transformation [4].

The iterative processing implemented in the AROP package allows us to process satellite images of different data quality. The iteration starts with by assuming the greatest geolocation accuracy using lowest (zero) degree polynomial function. If verification fails, it proceeds with a lower expectation using higher (1 or 2) degree polynomial function. The iterative processing always applies the minimum required degree of polynomial transformation and can preserve original image quality.

4 TESTING

The AROP package provides three operation options: standalone precision registration, standalone orthorectification, and combined operation. Users may choose to perform separate registration processes using the orthorectified image as the base image. If the warp image has already been precisely registered, then the AROP package can perform sole orthorectification on the warp image. If the warp image needs to be both precisely registered and orthorectified, then the AROP package provides a combined option. The combined option is suggested for orthorectification even if the warp image has already been precisely registered, since this option provides a better co-registration result for the base image and the warp image.

4.1 Combined precise registration and orthorectification

4.1.1 Factors Affecting Registration Accuracy

Better registration accuracy is expected using the base image acquired from the same season. Land cover changes between the base and the warp image may have some effect on tie point searching. However, as tie point seeds are initialized systematically at an adjustable equal distance, enough tie points can be found from images acquired in different seasons by adjusting seed distance (see Appendix A.2). In Fig. 5, we use Landsat GeoCover data (path 17 and row 34, western Virginia, USA) acquired on June 10, 2000 as the base image (Fig. 5a) to co-register and orthorectify a warp image acquired on November 1, 2000 (Fig. 5b). The median elevation for this area is around 800 meters. Land cover and seasonal changes are obvious in Figs. 5a and 5b. However, enough tie points (red crosses with circles) can still be found between the two images (seed distance = 50).

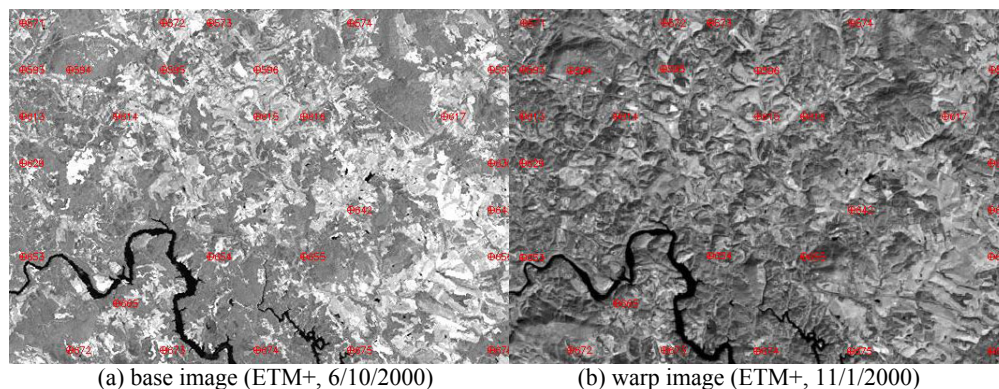


Fig. 5. Enough tie points (red crosses with circles) were found between Landsat ETM+ images (sub-scene of path 17 and row 34, Virginia, USA) acquired in different seasons based on band 5 data, despite the changing land cover, vegetation phenology, and data quality.

Cloud coverage may also affect tie point searching. Our tests show that the AROP can find tie points under thin cloud situations as illustrated in Fig. 6. In this test, we use Landsat

TM GeoCover data (path 15 and row 33, Delaware, USA) acquired on May 16, 1987 as the base image (Fig. 6a) to co-register and orthorectify a cloudy Landsat ETM+ image acquired on December 3, 1999 (Fig. 6b). Elevation in this area (close to sea level) is not a major factor for the image distortion. When the control chip size (default value of 11 pixels) is smaller than the cloud or aerosol spatial variation, the tie points with initial seed distance of 50 pixels detected from thin cloud area are still reliable.

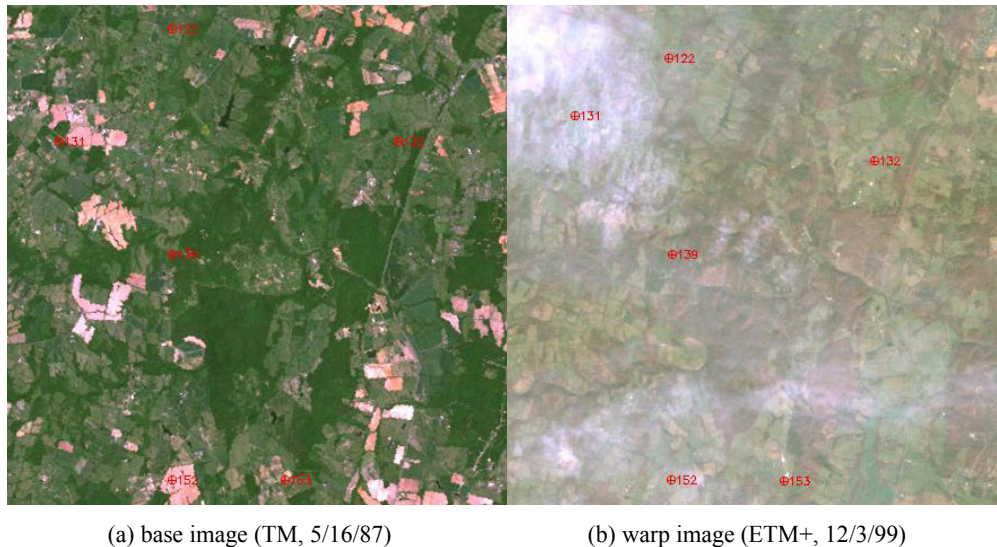


Fig. 6. Tie points (red crosses with circles) can be detected reliably under thin cloud conditions in this Landsat sub-scene (path 15 and row 33, Delaware, USA). Thin clouds are obvious in the RGB true color composite image (b).

4.1.2 Using a fine resolution image as the base image

Typically, a warp image is registered and orthorectified using the base image acquired from the same sensor. In this case, the base and warp images have close spatial resolutions, the same projection, and similar spatial coverage. In situations where the base and warp images come from different sensors, they typically have different spatial resolutions. The AROP package allows us to choose a fine resolution image as the base image to co-register and orthorectify the coarse resolution warp image in the working space. We can produce better geolocation accuracy using a fine resolution image as the base image. For example, we can use a GeoCover Landsat TM/ETM+ as the base image to co-register and orthorectify MSS images, which results in better geolocation accuracy than using a GeoCover Landsat MSS image as the base image.

4.1.3 Using a coarse resolution image as the base image

Under some situations, we do not have images with fine spatial resolutions. The AROP package allows us to use the coarse-resolution image as the base image. For example, we can use GeoCover Landsat TM/ETM+ data as the base image to co-register and orthorectify ASTER images if the orthorectified ASTER image for this area is not available. Fig. 7 shows the different co-registration and orthorectification results using coarse resolution images and fine resolution images as the base image (sub-scene of path 17 and row 34, western Virginia, USA). The median elevation for this area is around 1000 meters. In the figure, the coarse resolution Landsat base image is aggregated from the fine resolution Landsat ETM+ image. Fig. 7a shows the result of the Landsat ETM+ band 5 using the original resolution Landsat

ETM+ data as the base image. Figs. 7b and 7c use coarse resolution that is two and four times that of the original Landsat ETM+ resolution, respectively. The same DEM data from the Shuttle Radar Topography Mission (SRTM) were used as terrain elevation in the correction. Figs. 7b and 7c show the differences in band 5 using a coarse resolution image as the base image. Fig. 7b shows a smaller difference than Fig. 7c, which implies that better geolocation accuracy can be achieved using a fine resolution image as the base image during precise registration and orthorectification.

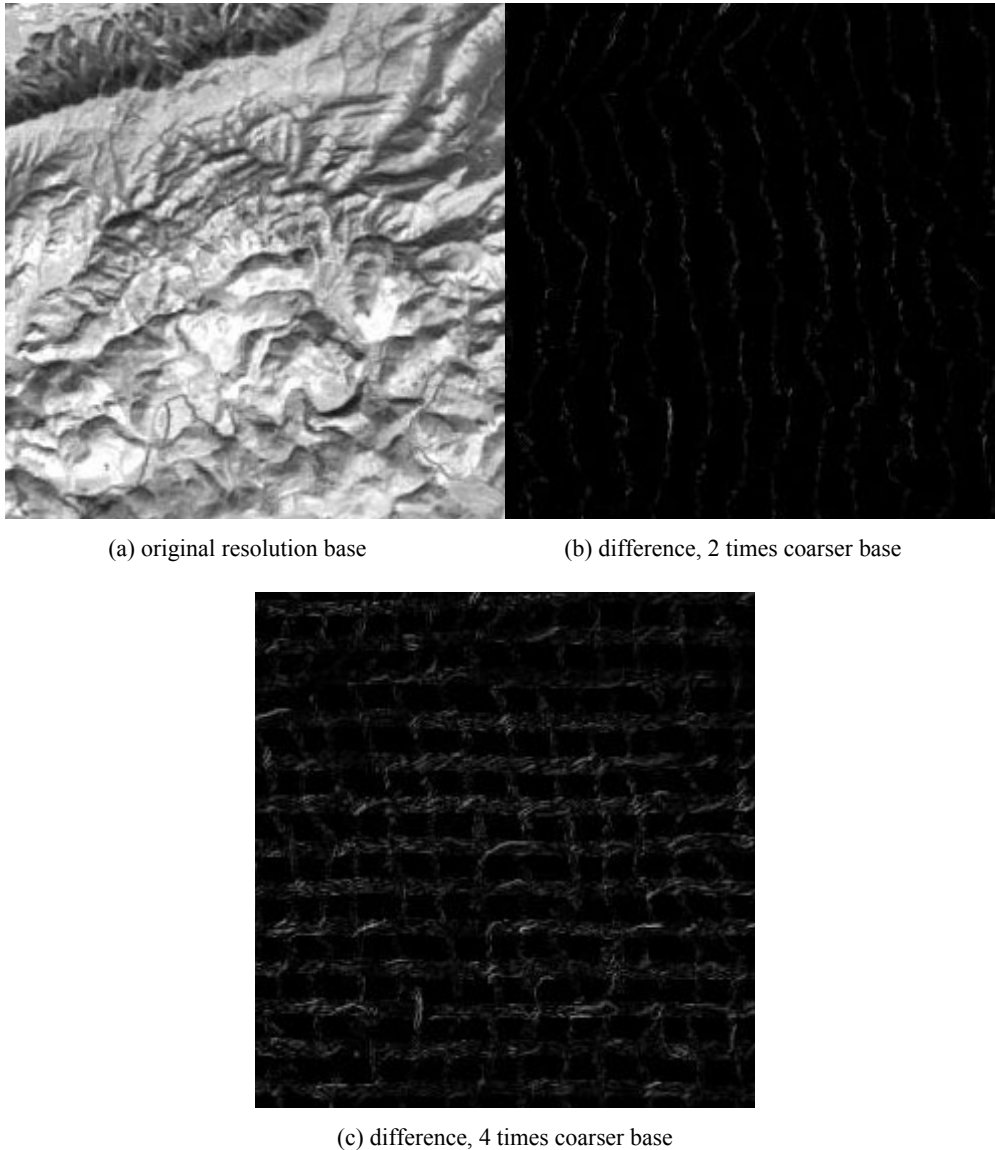


Fig. 7. The orthorectified Landsat ETM+ image (band 5) using original GeoCover Landsat ETM+ data as the base image (a) compared to the results using the coarse resolution base image. Figures (b) and (c) show the difference maps of the orthorectified result using the original resolution image as the base image compared to using coarse resolution images that are two and four times that of the base image, respectively.

4.1.4 Handling the warp image at different projections and map orientations

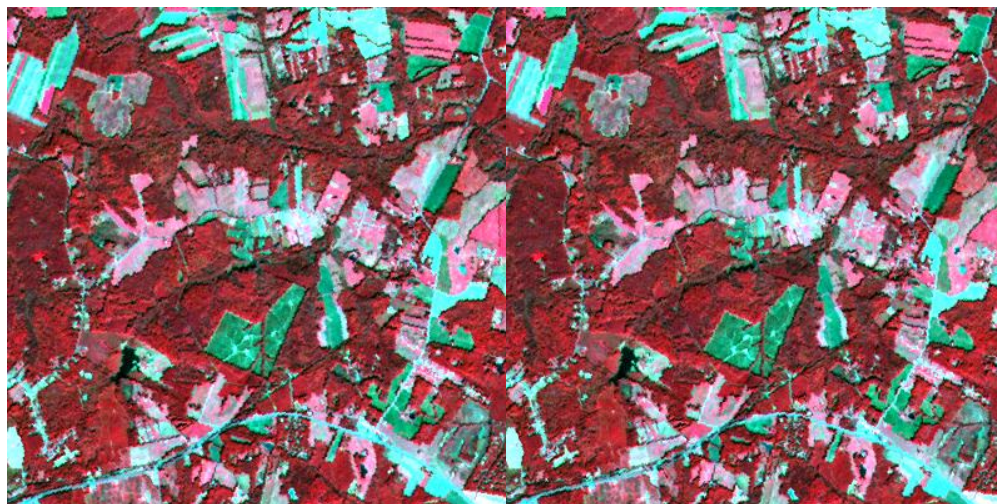
The AROP package assumes that the base image is saved in the UTM projection. However, the warp image may have different projections or UTM zone numbers. Some warp images need to be rotated from the satellite swath orientation to the "north-up" map orientation before reprojection, co-registration, and orthorectification. This situation requires multiple resampling processes. Using the combined resampling strategy in the AROP package, the final registered and orthorectified outputs are resampled only once from the original warp image. Fig. 8 shows the combined resampling strategy implemented in the AROP package as comparing to multi-resampling processing. In the figure, ASTER sub-scene (central Virginia, USA) were used for the testing. This area shows a mixture of cropland and forest types. The combined resampling strategy can provide more accurate result in geolocation and radiance than multi-resampling processing especially for the areas with complex landscapes.

4.2 Standalone precise registration

Some data sets have already been orthorectified. However, two orthorectified images may not match well for various reasons [4]. The AROP package provides the option to run a separate precise registration process. As in the combined process, precise registration first attempts to shift the upper left coordinate in order to avoid resampling. If the AROP fails, then it attempts a higher degree polynomial transformation through the iterative process. This option is also useful for co-registering two L1G images that have not been orthorectified, given that their nadir paths are close. Terrain elevation information is not necessary for this option.

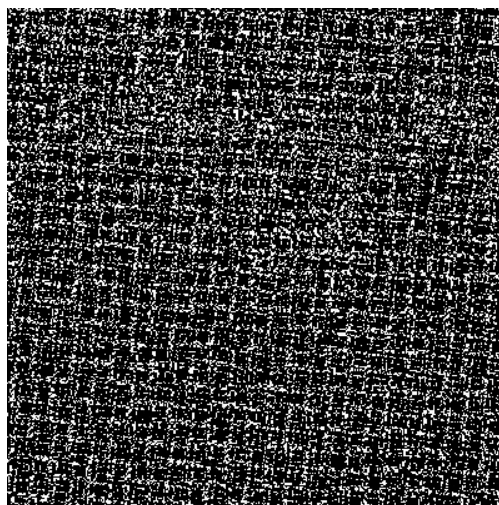
4.3 Standalone orthorectification

For data sets that have already been precisely registered, the AROP package provides the option to perform standalone orthorectification. Users do not need to supply the base image, since image matching verification will not be performed with this option. This option is suggested for the warp image that has been precisely registered with high accuracy.



(a) resampled once

(b) resampled 3 times



(c) difference

Fig. 8. This example shows an ASTER sub-scene (central Virginia, USA) using the AROP combined resampling strategy (a) and multi-resampling processing (b) both with the nearest neighbor resampling method. Multi-resampling processing in (b) includes rotation, reprojection and orthorectification. Although the RGB color composite images ($R=0.76\ \mu\text{m}$, $G=0.63\ \mu\text{m}$, $B=0.52\ \mu\text{m}$) (a) and (b) look similar, the difference map (c) between them for near-infrared band ($0.76\ \mu\text{m}$) reveals the variations of geolocation and radiance due to the different resampling strategies. In Figure (c), the white and grey areas refer to different resampling locations (and so radiance), and the black areas refer to the same location and radiance.

5 SUMMARY

This paper develops an automated precise registration and orthorectification package (AROP) for Landsat and Landsat-like data processing. The Landsat and Landsat-like satellite images acquired from different sensors at different spatial resolutions and projections can be re-projected, co-registered, and orthorectified to the same projection, geographic extent, and spatial resolution using a common base image; this allows us to perform multi-temporal image analysis directly. The AROP package combines reprojection, rotation, co-registration, and orthorectification into one resampling process and thus reduces the information loss due to multiple resamplings and is more efficient comparing to most commercial software. This package is suited for batch processing on a large amount of Landsat and Landsat-like data and has been tested and used in several projects, such as the Landsat time-series stack project [4] and a recent NASA EOS project using ASTER and Landsat data for forest change detection. We found that approximately two-thirds of the Landsat TM/ETM+ scenes and nearly all ASTER scenes required only one processing iteration; only one-third required second registration and orthorectification iteration with first degree polynomial transformation. The AROP package is now freely available from our research web site.

APPENDIX A: PARAMETER FILE DETAIL

A.1 Input parameter file

The input parameter file defines the base, warp, and output orthorectified images. The base image and the matching band from the warp images are used for the area-based tie point searching process. Although any band can be used for tie point searching, the informative

near-infrared or mid-infrared band (e.g., Landsat TM/ETM+ bands 4 and 5) are most appropriate. If the input file is saved in GeoTIFF format, the AROP package will extract the image size and related geo-reference information and then replace the user's definition in the input parameter file. A complete input parameter file should start with "PARAMETER_FILE" and conclude with "END". It includes the following parameters:

```
PARAMETER_FILE
#####
# define base image
#####
# define input file type, use GEOTIFF or BINARY
BASE_FILE_TYPE = GEOTIFF
# number of samples (columns) or use value from GEOTIFF file (-1)
BASE_NSAMPLE = -1
# number of lines (rows) or use value from GEOTIFF file (-1)
BASE_NLINE = -1
# pixel size in meters
BASE_PIXEL_SIZE = 28.5
# upper left coordinate in meters or use value from GEOTIFF file (-1)
BASE_UPPER_LEFT_CORNER = -1, -1
# base image for "r" and "b" options (one band)
BASE_LANDSAT = p015r034_7t19990930_z18_nn50.tif
# base image must be in UTM projection for this version
# use positive UTM for North and negative for South
UTM_ZONE = 18
# supported satellites: Landsat 1-5 and Landsat 7
BASE_SATELLITE = Landsat7
#####
# define warp images
#####
# define input file type, use GEOTIFF or BINARY
WARP_FILE_TYPE = BINARY
# number of samples (columns)
WARP_NSAMPLE = 4980
# number of lines (rows)
WARP_NLINE = 4200
# pixel size in meters
WARP_PIXEL_SIZE = 15.0
# upper left coordinate can be in meters or degrees (only need one)
# define upper left coordinate in meters
# WARP_UPPER_LEFT_CORNER =
# define upper left coordinate in degrees
#WARP_UPPER_LEFT_CORNER_DEGREE = -78.509630, 37.575253
# supported satellites: Landsat 1-5, Landsat 7, TERRA, CBERS1, CBERS2, AWIFS
WARP_SATELLITE = TERRA
# sensor pointing angle in degrees (for ASTER)
WARP_SATELLITE_POINTINGANGLE = 5.674000
# map orientation angle in degrees for warp image
WARP_ORIENTATION_ANGLE = -9.049154
# number of input bands
WARP_NBANDS = 9
# list each band filename separated by comma
```

```

WARP_LANDSAT_BAND =
AST_L1B_00310232005160936_20060603020838_7406.b1,
AST_L1B_00310232005160936_20060603020838_7406.b2,
AST_L1B_00310232005160936_20060603020838_7406.b3,
AST_L1B_00310232005160936_20060603020838_7406.b4,
AST_L1B_00310232005160936_20060603020838_7406.b5,
AST_L1B_00310232005160936_20060603020838_7406.b6,
AST_L1B_00310232005160936_20060603020838_7406.b7,
AST_L1B_00310232005160936_20060603020838_7406.b8,
AST_L1B_00310232005160936_20060603020838_7406.b9
# define data type for each band in: 1=8-bit; 2=16-bit
WARP_BAND_DATA_TYPE = 1 1 1 1 1 1 1 1 1
# define matching warp band to BASE_LANDSAT
WARP_BASE_MATCH_BAND =
AST_L1B_00310232005160936_20060603020838_7406.b4
# define projection for warp image if different from base image
# don't need these information if warp image projection is same as base
# define projection in GCTPC format (see GCTPC documents for details)
# 0=GEO; 1=UTM (default: UTM)
WARP_PROJECTION_CODE = 1
# use positive UTM for North and negative for South
WARP_UTM_ZONE = 17
# 15 GCTPC projection parameters (default: 0.0; not required for UTM)
# WARP_PROJECTION_PARAM =
# 0=radians; 1=US feet; 2=meters; 3=seconds of arc; 4=degree of arc
# 5=international feet (default: meters)
WARP_UNIT = 2
# 0=Clarke 1866; 8=GRS 1980; 12=WGS 84 (default: WGS 84)
WARP_DATUM = 12
#####
# define output images
#####
# define output pixel resolution
OUT_PIXEL_SIZE = 28.5
# define resampling approach (NN, BI, CC, AGG)
# NN for nearest neighbor,
# BI for bilinear interpolation
# CC for cubic convolution
# AGG for pixel aggregation
RESAMPLE_METHOD = AGG
# define image extent for the output (BASE, WARP, DEF)
# BASE uses base map extent
# WARP uses warp map extent
# DEF takes user defined map extent
OUT_EXTENT = WARP
# if DEF is defined, the following two lines need to be defined (in meters)
# OUT_UPPER_LEFT_CORNER =
# OUT_LOWER_RIGHT_CORNER =
# define corresponding output files for each band separated by comma
OUT_LANDSAT_BAND =
Ortho.AST_L1B_00310232005160936_20060603020838_7406.b1,
Ortho.AST_L1B_00310232005160936_20060603020838_7406.b2,

```

```

Ortho.AST_L1B_00310232005160936_20060603020838_7406.b3,
Ortho.AST_L1B_00310232005160936_20060603020838_7406.b4,
Ortho.AST_L1B_00310232005160936_20060603020838_7406.b5,
Ortho.AST_L1B_00310232005160936_20060603020838_7406.b6,
Ortho.AST_L1B_00310232005160936_20060603020838_7406.b7,
Ortho.AST_L1B_00310232005160936_20060603020838_7406.b8,
Ortho.AST_L1B_00310232005160936_20060603020838_7406.b9
    # define one corresponding output matching band for geolocation verification
    # define one band matching to BASE_LANDSAT
    OUT_BASE_MATCH_BAND =
Ortho.AST_L1B_00310232005160936_20060603020838_7406.b4
    # the maximum degree of polynomial transformation (0, 1, 2)
    # note that 2nd degree is not recommended unless have to
    OUT_BASE_POLY_ORDER = 1
    # ancillary inputs for orthorectification process
    # define terrain elevation file (must be in GeoTIFF format)
    # the SRTM DEM data in GeoTIFF format can be downloaded from the UMD GLCF
    INPUT_DEM_FILE = SRTM_u01_p015r034.tif
    # define projection for DEM data if it's different from base image
    # projection information is not needed if projection for DEM data is same as base image
    # define projection in GCTPC format (see GCTPC documents for details) (default: UTM)
    # DEM_PROJECTION_CODE =
    # use positive UTM for North and negative for South
    # DEM_UTM_ZONE =
    # 15 GCTPC projection parameters (default: 0.0)
    # DEM_PROJECTION_PARAM =
    # 0=radians; 1=US feet; 2=meters; 3=seconds of arc; 4=degree of arc
    # 5=international feet (default: meters)
    # DEM_UNIT =
    # 0=Clarke 1866; 8=GRS 1980; 12=WGS 84 (default: WGS 84)
    # DEM_DATUM =
    # tie point searching control parameters file (defined separately)
    CP_PARAMETERS_FILE = lndortho.cps_par.ini
END

```

In this example, we orthorectify and register ASTER Level 1G data (15m) using GeoCover Landsat ETM+ and aggregate them to GeoCover ETM+ resolution (28.5m). Note that the ASTER shortwave-infrared (SWIR) bands were enlarged from 30m to 15m resolution beforehand; this allows visible and near-infrared (VNIR) and SWIR bands to be processed together. The orthorectified and precision registered ASTER image matches Landsat GeoCover image very well. There are 1308 tie points found within a sub-pixel error among all 1402 detected tie points. The matching test in four quadrants is returned in (numbers of matching tie points / numbers of total tie points) as follows: upper left: (349 / 368); upper right: (327 / 352); lower left: (320 / 343); and lower right: (312 / 339).

We provide several testing cases in this package (see "readme" file). Users can download Landsat testing scenes from the Global Land Cover Facility (GLCF) web site at the University of Maryland as instructed in the "readme" file. The testing data include GeoCover Landsat TM and ETM+ data; Landsat L1G MSS, TM, and ETM+ data; the SRTM DEM; and ASTER data. The orthorectified outputs are saved in binary format with associated ENVI headers.

A.2 Tie point control file

Criteria for tie point searching and selection are defined in the tie point control file. The tie point control file appears in the input parameter file with the keyword "CP_PARAMETERS_FILE". The AROP package will use the default values (as provided in the text) if this file is not defined or does not exist. The preliminary registration is based on the coarse resolution image aggregated from the original fine resolution image. The aggregation scale is defined by the keyword "COARSE_SCALE". We suggest turning preliminary registration on if the geolocation accuracy of input warp image is bad or not defined. The initial tie point seeds are controlled by the interval distance. A smaller distance between seeds contains more tie point seeds.

```
PARAMETER_FILE
# 1 = use preliminary registration based on coarse resolution images
# 0 = not use preliminary registration
PRELIMINARY_REGISTRATION = 1
# aggregation scale of coarse resolution image to be used for preliminary registration
COARSE_SCALE = 10
# maximum shift that can be detected from preliminary registration
# equals to COARSE_SCALE*COARSE_MAX_SHIFT in fine resolution image
COARSE_MAX_SHIFT = 100
# interval distance (in pixels) for placing initial tie points for preliminary registration
COARSE_CP_SEED_WIN = 5
# control chip size (in pixels) for matching test
CHIP_SIZE = 11
# interval distance (in fine pixels) for placing initial tie points for precise registration
# smaller distance contains more tie point seeds
CP_SEED_WIN = 100
# maximum possible shift (in fine pixels) between base and warp images
# void if "PRELIMINARY_REGISTRATION = 1" (program will reset it automatically)
MAX_SHIFT = 50
# allowed number of high correlation matching in searching range
MAX_NUM_HIGH_CORR = 3
# minimum acceptable correlation coefficient for a matching tie point
ACCEPTABLE_CORR = 0.60
# minimum required number of control point for registration attempt
MIN_ACCEPTABLE_NCP = 10
# maximum allowed average error (in pixel) for precise registration
MAX_AVE_ERROR = 0.5
# maximum number of iterations if tie point testing fails
MAX_NUM_ITER = 1
# maximum acceptable RMSE for tie points
MAX_ACCEPTABLE_RMSE = 0.75
END
```

Acknowledgments

This work was supported by the US geological survey (USGS) Landsat Science Team project, the NASA LDCM data blender project, the NASA ACCESS LC-ComPS project, and the NASA EOS project. The authors would like to thank Dr. Dan Slayback, Dr. Chengquan Huang, and Mr. Teng-Kui Lim for their feedback and suggestions while testing and running the AROP package.

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Feng Gao is a senior scientist at the Earth Resource Technology Inc. and the NASA Goddard Space Flight Center. He received the B.A. degree in geology and the M.S. degree in remote sensing from Zhejiang University, Hangzhou, China, in 1989 and 1992, respectively, the Ph.D. degree in geography from Beijing Normal University, Beijing, China, in 1997, and the M.S. degree in computer science from Boston University, Boston, MA, in 2003. He is the author of more than 40 journal papers. His current research interests include remote sensing modeling, multisensor data fusion, and retrieving vegetation parameters through remotely sensed data.

Jeffery G. Masek received the B.A. degree in geology from Haverford College, Haverford, PA, in 1989, and the Ph.D. degree in geological sciences from Cornell University, Ithaca, NY, in 1994. He is currently a Research Scientist in the Biospheric Sciences Branch, National Aeronautics and Space Administration Goddard Space Flight Center, Greenbelt, MD. His research interests include mapping land-cover change in temperate environments, application of advanced computing to remote sensing, and satellite remote sensing techniques. He also serves as Deputy Project Scientist for the Landsat Data Continuity Mission and has held previous positions at University of Maryland, Hughes Information Systems, and Cornell University.

Robert E. Wolfe works in the Terrestrial Information Systems Branch at NASA Goddard Space Flight Center. For over 12 years, he has led Moderate Resolution Imaging Spectroradiometer (MODIS) geolocation activities, coordinated the MODIS Land science discipline activities, and participated in the evolution of the MODIS Data Processing System (MODAPS). He is currently co-chair of NASA's Earth Science Data Systems Software Reuse Working Group, is NASA's Terra Deputy Project Scientist for Data, is a key participant in the Land PEATE and NICSE activities of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP), and participates in projects studying terrestrial biophysics over North America. Mr. Wolfe has B.S. degrees in physics and mathematics from Bridgewater College and over 27 years of experience in Earth remote sensing.